

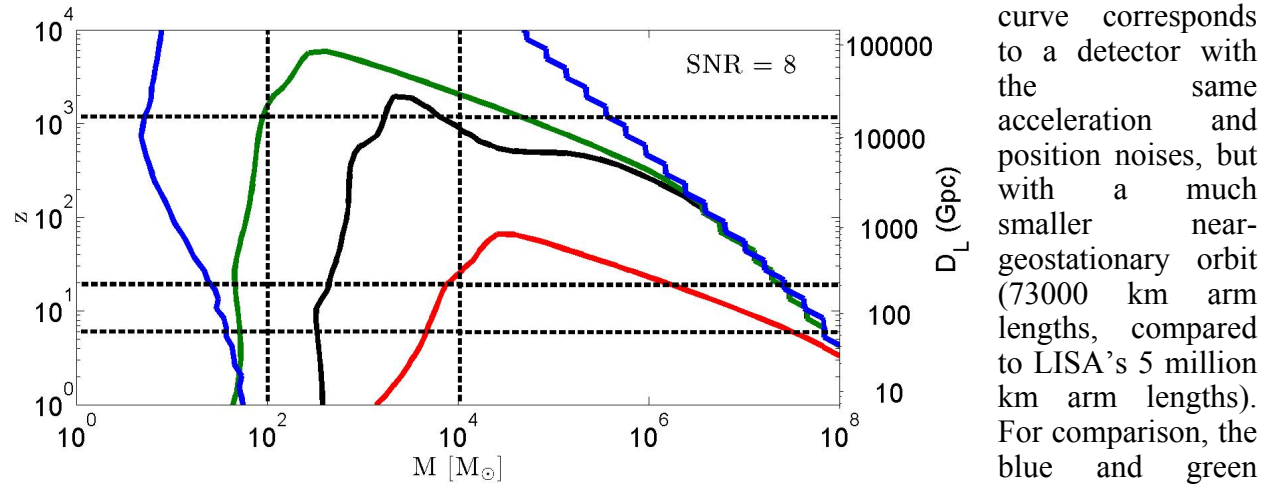
MILLIHERTZ TO DECIHERTZ GRAVITATIONAL WAVE ASTRONOMY

Precise space-based interferometric probes of the Universe's first black holes

The *New Worlds, New Horizons* Decadal Survey identified Gravitational Wave Astronomy as a science priority in the coming decade, particularly its ability to probe massive black holes (MBHs) with phenomenal accuracy. The focus of the LISA science case as it pertains to MBHs focuses on LISA's ability to precisely measure the source parameters of individual systems, and to constrain the history of hierarchical structure formation through the characterization of the full population of merging sources at $1 < z < 20$. By measuring the parameters, particularly the masses, of MBHs in this epoch, we can constrain the characteristics of the earliest "seed" black holes that provided the building block of the later massive black holes through some combination of accretion and merging.

However, on time scales beyond ~ 10 years, improved technology in the form of enhanced disturbance reduction, more powerful lasers, and improved suppression of other position noises would facilitate not only far greater accuracy in measuring the complete population of merging MBHs, but also the direct observation of seed black holes in the earliest era of structure formation.

In the figure, we show contours inside which an optimally-oriented and located equal mass, nonspinning MBH binary with the given local rest mass and redshift/luminosity distance can be detected with $\text{SNR} > 8$. The black curve corresponds to the original LISA designs, and the red



curves show a future generation of observatories with LISA and near-geostationary orbits, respectively, but with increased laser power, an improved disturbance reduction system, and suppression of the full position noise budget to the level of the shot noise, such that the full amplitude spectral noise density is lowered by two orders of magnitude.

Whereas original LISA could probe the high end of the theoretical mass of seed black holes, which is $10^4 M_{\text{Sun}}$ at $z > 20$, both the future LISA and the future near-geocentric observatories can probe down below $10^2 M_{\text{Sun}}$, to the lowest masses theoretically expected for seed black holes. Furthermore, both future observatories would be sensitive to the full range of seed masses out to vast distances, beyond even the epoch of recombination at $z \sim 1100$. The future LISA would be sensitive to MBH binaries with masses in the range $5 - 10^4 M_{\text{Sun}}$, far beyond recombination, and far beyond the point where ΛCDM would predict that stars could exist and evolve to black holes. Therefore, the future LISA design would provide an unambiguous probe of primordial black holes. Since the CMB provides no constraints on structure at the length scales of MBHs, gravitational waves could provide a unique probe of this epoch on very small length scales.

